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Meeting Paper

General Overview and Research Recommendations
for
Caven Sealing and Abandonment Research Program

by

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General Overview and Research Recommendations

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Introduction

Abandonment of sealed liquid filled salt caverns has been a question for industry and regulators from many years. It has been the focus of many technical papers, symposia, conference panels, field experiments, lab experiments, etc., over the last 10 to 20 years. The recently completed "SMRI Bibliography for Cavern Abandonment" is an up to date source of references to the relevant literature.

Although there is perhaps a general agreement on the gross scenario of concern, there is certainly differences in opinion by the many "technical experts" on the details related to salt cavern pressurization following abandonment or plugging, and the salt response to the cavern pressurization. Bringing such differences of opinion into a more focused level of understanding is the overall purpose of the SMRI Cavern Sealing and Abandonment Research Program (CS&ARP).

Technical Background

Cavern sealing of liquid filled salt caverns is intended to generally include the long term isolation or plugging of salt caverns which contain sufficient liquid content that pressure within the cavern is communicated within the cavern by the fluid. The liquid could include fluids such as brine which are generally treated as incompressible fluids, or materials such as air, which act as a compressible "liquid."

Long term isolation or plugging is the act(s) of hydraulically isolating the cavern from the access well or entry point. Usually this is the simple act of "packing off" or inserting a "plug" into a well(s) casing, and filling the well or casing with significant sections of concrete, or cement grouts. Other plugging systems which address very long time periods (hundreds or thousands of years) have also been proposed. These include natural materials such as bentonites, salts, etc.

Following isolation or plugging, a salt cavern will deform according to the physics of what is known or termed salt creep. In general, this is a process whereby the salt acts like a visco plastic type material slowly deforming towards a state of uniform stress. More simply stated, cavern walls slowly move inward or "close" if the internal wall pressure exerted by the liquid is less than the external salt lithostatic pressure, and move outward or "open" if the internal liquid pressure is greater than the salt lithostatic pressure.

Under the normal scenarios of cavern plugging, the liquid within the cavern is less dense than the salt. As such, the "pressure gradient" within the cavern is not as great as the lithostatic pressure gradient within the salt external to the cavern i.e., the lithostatic pressure in the lower portion of the cavern will be higher relative to the liquid pressure in the lower portion, than the lithostatic pressure in the upper portion relative to the liquid pressure in the upper portion. The magnitudes of the differences depend on the density of the liquid and the height or vertical dimensions of the cavern. As stated earlier, the salt will creep inward if the liquid pressure is less than the salt lithostatic pressure, and the rate of salt creep is known to be closely modeled by the magnitude of the pressure difference to the approximately 5^{th} power. The salt will creep outward if the internal liquid pressure is greater than the external lithostatic pressure.

Mathematical models of salt creep have been developed by several researchers (see references in Appendix 2 "Creep Behaviour of Rock Salt [1]). These are mathematical models usually fit to laboratory or field data, and typically contain parameters such as temperature and stresses within the salt. Additionally, details of the pressure or stress history sometimes are included. Although variations between models exist in the details of the models, most models are sufficiently similar that for purposes of understanding sealed caverns, the differences may generally be ignored. One important aspect of salt creep behavior, which may not universally be agreed upon, is the salt creep response to very small stress differences. Such response has been historically very difficult to measure in the laboratory since extended periods of time (years) are necessary to observe very small creep rates. The existence of such creep has been argued from anecdotal evidence of observations of concave ceilings or roofs, and walls in very shallow old salt mines. For the purposes of the CS&ARP, we will assume that salt creeps at all nonzero stress differences, or that the height of the cavern is sufficient that the stress differences are' of sufficient magnitude that the cavern never reaches a static equilibrium state.

Following plugging or sealing of a cavern well(s) or entry(s), pressurization (or depressurization) of the liquid will occur due to salt creep, and thermal expansion (or contraction). Normally, due to convenience during the plugging process, the cavern is plugged with the liquid pressures well below the lithostatic pressure within the cavern (e.g., zero or minimal liquid pressure at the surface above the cavern). Depending on the temperatures of the liquid and surrounding salt, the liquid may expand or contract with time as the liquid and salt come to thermal equilibrium. Typically, the salt is warmer and the liquid is slowly heated, requiring many years for the cavern to come to thermal equilibrium with the salt in larger salt caverns. The thermal properties of liquids and salt are known or can be adequately established with standard laboratory tests, and thermal models of "idealized" cavern shapes have been published.

Liquid pressurization within the cavern and the salt response is the focus of the CS&ARP. Theoretically, the salt creep (and thermal expansion) will increase the fluid pressure at the top or in the upper part of the cavern to or above the lithostatic pressure in the salt (at the corresponding height) if the liquid is contained within the cavern. As the pressure increases, potential loss of fluid from the cavern could occur if the permeability of the salt is sufficiently high, if the salt fractures and creates a flow path for the liquid, or if the salt / well interface leaks or allows fluid to flow. The CS&ARP is intended to focus analytical and experimental resources to establish which mechanisms and under what conditions, if any, could liquid leave a cavern.

Fluid Loss Mechanisms

Salt Permeability:

Permeability within the salt structure or within components of the structure such as bedding planes offer a potential path for fluid loss. Permeability of salt can also change or be modified as a result of confining pressure. Permeability has been studied by multiple authors [SMRI Bibliography for Cavern Abandonment - Authors listed in Appendix 2, Sections 5 "Permeability at isotropic stress", 6 "Permeability at high deviatoric stress", 7 "Permeability at liquid pressure above confining pressure", and 8 "Interdependence rock stress / permeability"]. As noted in the SMRI Bibliography [1], much of the work on permeability of salt has been done for the nuclear waste disposal programs. Much of the referenced work is concerned with permeability changes at high deviatoric stresses. Salt damage models have also been developed. These models relate "damage" to deviatoric stress levels integrated over time. These models have been particular useful in studying salt mine surfaces, or cavern surfaces for caverns operated at low liquid pressures.

Fokker and Kenter [2,3] have advanced a theory.of an increasing salt permeability for the salt surrounding a cavern when the fluid pressure is greater than the lithostatic pressure. Conceptually, an increased salt permeability would provide the necessary flow path for liquid such that the liquid pressure would be limited to some value in excess of lithostatic but below fracturing pressures. Of question is the ultimate or final location of the liquid, and the time period. It is theoretically conceivable that the fluid contents of a cavern could be distributed over great distances within the salt given sufficiently long periods of time.

Salt Fracturing:

Salt fracturing due to increasing fluid pressures would also provide the necessary pressure relief to limit the pressure buildup within a cavern. Experimental studies conducted by Thorns [4], and others have demonstrated the confining pressure and rate dependence of hydrofracturing. In general, the rates measured in in situ tests in wellbores are general greater than the rates expected for caverns naturally pressurizing, even with a significant thermal fluid expansion component. However, given a cavern with a sufficiently large vertical dimension and a fluid with a density sufficiently less than salt, in the absence of other fluid limiting phenomena, the salt could theoretically be fractured. Most studies to date do not conclude that the conditions will be present for this mechanism to occur.

Wellbore Seal:

For short term or even moderate term plugging (tens of years), concrete or cement grout plugs within wellbores have been demonstrated. Longer term plugging (hundreds or thousands of years) may require natural materials which do not degrade with time.

Programs such as WIPP have extensively studied long term plugs, even plugging materials for mine shafts. Since the requirements for sealing wellbores for cavern abandonment, are a definite subset of requirements for sealing salt nuclear repositories, it is felt that current Orders, and Regulations, and the R&D efforts of the nuclear waste disposal programs will provide sufficient near and long term technical solutions to sealing the wellbores internally. Concrete or cement grouts are typically found immediately outside the steel (or other material) casing within the well. Such materials are used to seal the casing material to the salt. While it is recognized that the lifetime of such material is finite (30 - 100+ years, the lifetime is still long compared to the cavern pressurization period (generally modeled as less than tens of years). Hence the CS&ARP will not include this area of investigation.

Of more question is the interface between the external wellbore concrete or cement grouts and the salt. The potential for this interface to leak under high cavern liquid pressures has been theorized for many years [5]. Several studies using finite element techniques have been conducted [6]. In these studies, the salt / concrete or cement grout interface is generally assumed to open up under tension conditions, i.e., no adhesion qualities within the salt. Theoretically, if tension conditions exist within the salt at the interface, the salt will pull away from the interface, allowing the liquid to enter. This effect proceeds up the interface from the cavern along the salt / concrete or cement grout interface (assuming a vertical well extending from the cavern upward). Characteristically, this has the hydraulic effect of extending the cavern vertical dimension, thus theoretically creating even greater overpressures as the liquid moves upward. This has occasionally been referred to as “zippering”.

While studies have identified the zipper effect as a potential sealed cavern leak mechanism, like all postulated cavern pressure limiting mechanisms, it has not been explicitly observed. In fact, no descriptions of experiments or tests have been found which were conducted with sufficient instrumentation and under the postulated conditions to validate or refute the hypotheses.

Field Data

As described by Behrendt, et al. [1], existing data on actual field experiments or tests are limited. A test was conducted in Germany in 1990/1991 in which a salt cavern was artificially pressurized. This test was well instrumented in terms of pressure and fluid injection rates. Other diagnostic data were also taken. Since the test was funded by a consortium, results of the test remain unavailable. SMRI is negotiating access to the data as part of the CS&ARP, however.

Other potentially applicable data was obtained by Durup [7] using wellbores. Van Sambeek [8] also reported on data from an abandoned solution well.

Background Conclusions

The state-of-the-art in understanding the behavior of sealed salt caverns might be summarized as follows:

- Models to predict the fluid thermal expansion or contraction, and material properties (or techniques to obtain them) are adequate.
- Models to predict the creep response of salt exist, although variations within the models exist. The models are judged adequate for prediction of the internal creep response of sealed salt caverns given the liquid pressure.
- Three fundamental mechanisms have been historically identified which could provide a mechanism for fluids to leave the salt cavern:
    1. Fluid loss through salt permeability
    2. Fluid loss through hydrofractures
    3. Fluid loss along the well cement / salt interface
- No data or test results are currently available which unequivocally validates or eliminates any of the potential fluid loss mechanisms under all conditions.
- Fluid loss mechanisms may vary depending on the properties of the salt (impurities, permeability), physical geometrys, and pressurization history.

SMRI CS&ARP Possible Research Approaches

1. Obtain data and conclusions from the referenced cavern pressurization test in Germany.
2. Conduct laboratory scale experiments to better understand the permeability/stress dependence of salt(s).
3. Conduct laboratory scale experiments to study the cement / salt interface stress dependence characteristics.
4. Conduct in situ wellbore scale liquid pressurization tests.
5. Conduct in situ cavern scale liquid pressurization tests.
6. Conduct "benchmark" analyses to validate key analytical results.

Key points to be considered relative to approaches are discussed below:

1. Negotiations for a firm offer for access to the German test data are expected to be complete very soon. Details of the test will be included with the offer. It is expected that the analyses completed to explain the results will also be included. However, as with any test, those analyses need to be validated, or at least carefully reviewed.

2. Some laboratory scale experiments on enhanced permeability in salt at elevated stress levels have been reported [3]. These are potentially very important in the overall understanding of sealed cavern responses. It is important to validate changes in permeability and to understand the extent and final disposition of the fluid which "left" the cavern.

3. The loss of cavern fluid along the cement / salt interface has been hypothesized based on general characteristics of salt. It might be feasible to conduct limited laboratory scale tests to validate aspects of the theory.

4. Wellbore scale liquid pressurization tests were conducted by Gaz De France. Additional tests might be conducted with address such questions as dependence on the particular salt or location tested, and provides more instrumentation to better support result interpretation. Such tests are potentially less expensive than cavern tests, and wells of opportunity may be more available. Such tests will still be in the $50K - $200K range potentially.

5. Cavern tests are the ultimate test. They are potentially very expensive, and may not provide conclusive or fully interpretable results. Typical cost considerations require that only "caverns of opportunity" be considered by the CS&ARP. Such issues as cavern integrity, site location, geometry, casing condition, etc., all must be considered. For the CS&ARP, it is recommended that such tests be considered if caverns of opportunity are proposed, and considered on their individual merit based on the circumstances. However, until other elements are better known it is recommended by the program manager that the CS&ARP not aggressively pursue full scale test opportunities.

6. "Benchmark" analyses may be the only valid approach to validating analytical results. Requesting that key analytical results by independently validated enables the CS&ARP to understand any result dependencies on assumed parameters, or models used. For example, are the analytical finite element results relative to the wellbore cement / salt interface dependent on codes, boundary assumption, material property assumptions, etc.?

Recommendations

The CS&ARP program manager was tasked with identification of key issues relative to cavern sealing. It was also tasked with developing options for research areas. It was not intended that the program manager would assess the validity of technical results, but would recommend potential research directions. The CS&ARP research committee would review those recommendations, and propose specific actions for SMRI funding or Proposals.

Recommended research:

- If the German test results can be obtained at a reasonable cost, it is recommended that SMRI secure the results.

- In order to validate the potential loss of cavern fluid through salt permeability, it is recommended that at least two other benchmark analyses be conducted. These analyses would have explicit salt constitutive relationships with pressure defined, cavern geometries defined, model boundary conditions defined, and liquid properties and pressure defined. It is envisioned that such analyses will not be cost prohibitive, and the results will identify assumption dependences, model dependences, or other areas which raise issues with acceptance of the results.

- In order to validate the theory of potential loss of cavern fluid through the cement / salt interface, it is recommended that at least two other benchmark analyses be conducted. These analyses would have explicit salt constitutive relationships with pressure defined, cavern and well geometries defined, model boundary conditions defined, and liquid properties and pressure defined. It is envisioned that such analyses will not be cost prohibitive, and the results will identify assumption dependences, model dependences, or other areas which raise issues with acceptance of the results

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